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The very local Hubble flow: computer simulations of dynamical history

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Abstract. The phenomenon of the very local (≤ 3 Mpc) Hubble flow is studied on the basis of the data of recent precision observations. A set of computer simulations is performed to trace the trajectories of the flow galaxies back in time to the epoch of the formation of the Local Group. It is found that the 'initial conditions' of the flow are drastically different from the linear velocity-distance relation. The simulations enable also to recognize the major trends of the flow evolution and identify the dynamical role of universal antigravity produced by cosmic vacuum.

Key words. galaxies: Local Group

1. Introduction

As is well-known, the original Hubble diagram plots galaxy kinematics for the distances within 20 Mpc, after the correction of a systematic error in the determination of distances. Sandage (1999) confirms that the Hubble flow takes its origin at very small distances, 1.5–2 Mpc, from the center of the Local Group (see also Ekholm et al. 2001). A recent high precision mapping of the very local velocity field has covered the spatial scales between 1.5–2 and 3 Mpc (Karachentsev et al. 2000, 2002, 2003). High precision has become possible due to remarkable progress in accurate distance measurements for galaxies in the vicinity of the Local Group (LG), — mostly due to observations with the *Hubble Space Telescope*. The velocity field has been found by Karachentsev and co-workers to have a fairy regular kinematical structure with the linear velocity-distance relation and the expansion rate of 72 ± 15 km/s/Mpc. The flow is rather cold: its one-dimensional mean random motion is about 30 km/s. The expansion flow on these spatial scales is referred to as the very local Hubble flow (hereafter VLHF).

In this paper, we use the recent precision data (Karachentsev et al. 2002) to follow the VLHF dynamical history. We have performed a set of computer simulations for the present, past and also future of VLHF. This enable us to re-construct the 'initial conditions' for VLHF at the epoch of the Local Group formation 12.5 Gyr ago and found that the observed fairly regular state of the flow is a result of the dynamical evolution from a highly disordered and violent initial state. We found that the initial state of VLHF resembles a model of the Little Bang proposed by Byrd, Valtonen, McCall and Innanen (1994) for the early Local Group. This state is in general agreement as well with a new picture of the Local Group formation discussed recently by van den Bergh (2003); this picture involves also violent dynamics as a key physical factor of the process.

In Sec.2, a theory background is discussed which takes into account the dynamical effect of newly discovered cosmic vacuum; in Sec.3, the basic data we use are summarized; the simulations are presented and analyzed in Sec.4; conclusions are given in Sec.5.

2. The Hubble-Sandage paradox

The phenomenon of VLHF has not been predicted by the cosmological theory. Moreover, the existence of the cosmological expansion in the local volume contradicts widely accepted cosmological concepts. Indeed, it has commonly been believed that the very notion of the cosmological expansion is applicable to only very large spatial distances, and so only when one reaches the scale of great clusters

of galaxies (100–300 Mpc) one should find the markers that participate in the cosmological expansion. An obvious reason for this is that the expansion with the linear velocity-distance relation is directly associated with the uniformity of the universe. And the matter distribution is uniform on the spatial scales larger than 100–300 Mpc. Observations reveal no uniformity in the nearby spatial distribution of galaxies, in the scale range from a few to 20 Mpc. Meanwhile, the cosmological expansion was originally discovered deep inside the cell of uniformity in the galaxy distribution.

A question arises: how the observed spatial non-uniformity of the galaxy distribution in the local volume may be compatible with the observed regular linear velocity field?

Sandage (1986; see also Sandage et al. 1972) was the first who discussed such a controversy, and, according to his recent conclusion, an "explanation of why the local expansion field is so noiseless remains a mystery" (Sandage 1999). It is also puzzling that the local rate of expansion is similar to the global one, if not exactly the same, within 10–15 percent accuracy (Sandage 1999).

The linear velocity-distance relation in local and global expansion flows and the almost (if not exactly) the same expansion rate (the Hubble parameter) in the both indicate that there is a common physical agent that affects the expansion flow from the distances of a few Mpc up to the observation horizon. It has been proposed (Baryshev, Chernin, Teerikorpi 2001; Chernin 2001, Chernin, Teerikorpi, Baryshev 2002; Chernin, Karachentsev, Teerikorpi 2003) that this physical agent is cosmic vacuum (or the cosmological constant, or dark energy) with its perfectly uniform energy density on all spatial scales. We have argued that this idea offers a possible solution to the Hubble-Sandage paradox that has existed in cosmology for more than 70 years.

Cosmic vacuum has been discovered in recent SN Ia observations (Riess et al. 1998; Perlmutter et al. 1999) confirmed by all the bulk of cosmological evidence (see for a fresh review Peebles and Ratra 2003). The vacuum density ρ_V comprises up to 70-75 percent the total density of the Universe. The dynamical effect of cosmic vacuum is enhanced by the fact that, according to the Friedmann theory, the effective gravitating (actually, antigravitating) density of vacuum is $\rho_V + 3p_V = -2\rho_V$, where $p_V = -\rho_V$ is the vacuum pressure.

Our suggestion above is invoked by Thim, Tammann, Saha, Dolphin, Sandage, Tolstoy and Labhard (2003) in a recent treatment of their new observations on the extreme quietness of the local (1–10 Mpc) expansion field. They also mention that the suggestion makes a continual precision mapping of the local velocity even more crucial.

3. Basic data on VLHF

In the dataset on the very local velocity field published by Karachentsev et al. (2002), there are 38 galaxies located within 3 Mpc. Two of them have no measured velocities yet; two other do not have estimated distances; six more have only low accuracy distances. Six of the rest with distances around 2.8 Mpc are located on the front side of the Canes Venatici cloud and apparently move from us toward the cloud center with an additional velocity of about 85 km s^{-1}. With their exclusion, the collection of 22 galaxies (including one located in the center of the Canes Venatici cloud) is accepted as the observational basis for the computer simulations. These galaxies may reasonably be considered as 'most typical representatives' for the very local Hubble flow (VLHF). Their names, distances and velocities relative to the center of the Local Group are given in Table 1 (columns 2–4). Note that the galaxy distances, R, are known with typical accuracy of 10%. The galaxies are small in mass (dwarfs) and fairly separated from each other, as is seen from both distances and position angles; because of this, their interaction with each other is negligibly weak compared to the interaction with the two major galaxies of the Local Group (hereafter LG) and vacuum (see below). The 22 galaxies reveal together the Hubble velocity-distance linear relation, $V = H_L R$, with the time rate $H_L = 72 \pm 15$ km s^{-1} Mpc^{-1} and the one-dimensional velocity dispersion 30 km s^{-1}. For more detailed data on the VLHF galaxies and their analysis (including a discussion of the accuracy of the observations) see in Karachentsev et al. (2002).

Table 1. Galaxies of the very local Hubble flow

N	Name	R Mpc	V km/s	R_0 Mpc	V_0 km/s
1	SagDIG	1.15	23	0.49	140
2	SexB	1.63	111	0.60	162
3	Antlia	1.70	66	1.23	188
4	N3109	1.70	110	1.16	167
5	SexA	1.74	94	0.69	177
6	KKR25	1.79	68	0.83	95
7	E294-010	1.92	81	0.82	104
8	KKH98	2.02	151	0.97	144
9	KK230	2.03	126	0.31	172
10	N300	2.11	114	0.62	140
11	UA438	2.16	99	0.92	109
12	I5152	2.18	75	1.27	77
13	GR8	2.37	136	0.60	178
14	U8508	2.55	186	0.15	221
15	I3104	2.62	171	0.49	214
16	N404	2.63	195	0.71	186
17	DD0187	2.69	172	0.56	190
18	DD0190	2.83	263	0.54	269
19	KKH86	2.92	209	0.33	231
20	GamB	3.00	266	0.45	268
21	N1560	3.05	171	1.08	156
22	N2403	3.09	268	0.31	277

4. Computer simulations

4.1. The model

We have developed a set of computer simulations in which individual galaxies of VLHF do not interact with each

other; the observational reason for this is seen from what was said in the section above. We also take into account that the mass of LG (including dark mass) is strongly concentrated (Karachentsev et al. 2002) to the two major galaxies of the group. We assume that dark matter halo of the Milky Way (MW) and the Andromeda Galaxy (AG) are spherical. The adopted total mass of MW is $1 \times 10^{12} M_\odot$ and the total mass of AG is $1.5 \times 10^{12} M_\odot$. In this statement of the problem, a galaxy of VLHF is considered moving in the gravity field of the two major galaxies of LG (including their dark matter haloes) and the antigravity field of cosmic vacuum. Therefore the computer simulations are reduced to the integration of the Newtonian restricted tree-body problem on the cosmic vacuum background, for each of the 22 galaxies of the Table 1. The galaxy velocities are assumed to be radial, at the present state of the flow.

Cosmic vacuum is represented in the simulations by a 'medium' with a perfectly uniform energy density which is also constant in time, as it follows from the Friedmann model. The concordance figure (see again for a review Peebles and Ratra, 2003) for the vacuum energy density is $\rho_V = (0.7 \pm 0.1)\rho_c$, where $\rho_c = 2 \times 10^{-29} h^2$ g cm^{-3} is the critical density estimated with the 'global' Hubble constant $h = H/100$ km s^{-1} Mpc^{-1}; $h = 0.65 \pm 0.10$. The present cosmic age is assumed to be 14 Gyr.

The simple Kahn-Woltjer model (Kahn and Woltjer 1959) for LG which assumes the straight linear relative motion of the two major galaxies of the group is re-computed with the account of the new data on the galaxy masses and the vacuum density. The present separation 0.7 Mpc and the relative velocity -120 km s^{-1} are adopted. The two major galaxies, MW and AG, started their motion toward each other 12.5 Gyr ago. In our computer simulations, the trajectories of the VLHF galaxies are traced back in time to that moment in the past. The trajectories are also computed for about 6 Gyr in the future, up to the moment when MW and AG come into contact collision.

Antigravity of cosmic vacuum dominates dynamically (it is taken into account that its effective energy density is $-2\rho_V$ — see Sec.2) during all the 12.5 Gyr history of the Local Group at the distances larger than 2 Mpc from the center of the group. This is one of the results of the computer three-body problem. The critical 'zero-gravity surface', i.e. the surface at which the radial component of the gravity and antigravity forces are exactly balanced, is showed in Fig. 1. It may be seen from the figure that the surface can be embedded completely between two concentric (centered to the center of the Local Group) spheres, one with the radius of 1.8 Mpc and the other 1.7 Mpc, at present. The two enveloping spheres have radii 2 Mpc and 1.6 Mpc in the past, 12.5 Gyr ago. Thus, the surface is nearly spherical, and it remains nearly unchanged during all the history of VLHF. Outside the zero-gravity sphere the potential is repulsive, and it can be considered as nearly spherically symmetrical and nearly static, with a good accuracy. This dynamical background determines the major features of the VLHF evolution, in our simulations.

The results of the simulations are presented in Table 1 and Figs. 2–4. In Table 1 (columns 5,6), the initial state of VLHF is described by the radial velocities and distances of the flow galaxies 12.5 Gyr ago. The dynamics of VLHF is illustrated by the VLHF phase portrait (Fig. 2) which consists of 22 evolutionary curves in the velocity-distance plot; these are the radial velocities and radial distances relative to the center of LG. The dynamical role of cosmic vacuum may be recognized from the comparison of the real phase curves with 'imaginary' phase curves that are computed for the same initial conditions 12.5 Gyr ago, but with no vacuum background. As one may see, a typical phase curve describes a decrease of the velocity with the growth of the distance from the LG center, at the first stage of the evolution. At the next stage, the velocity grows with distance under the action of the cosmic vacuum antigravity.

4.2. VLHF initial conditions: the Little Bang

The initial state of VLHF as is recognized from the simulations is drastically different from any naive expectations that could treat VLHF as a primeval cosmological flow that might be only slightly distorted initially. The radial velocities and radial distances of the galaxies at the initial moment 12.5 Gyr ago given in columns 5,6 of Table 1 suggest a conclusion that the initial state of VLHF has nothing in common with such a picture. The deviations from an imaginary 'unperturbed' initial flow that could exist on the same spatial scales at the same early time are very strong.

To examine how robust this conclusion may be, we have performed a special set of test simulations at which an additional transverse velocity is assumed that is 20–30 percent of the observed radial velocity of the galaxies at present. We also have repeated simulations with variations of the observed distances, R, within $\pm 10\%$. The result has demonstrated a good qualitative agreement with the basic conclusion about a highly perturbed initial state of the flow 12.5 Gyr ago, in both cases. The structure of the initial states in such test simulations differs from that of the basic simulation only in quantitative details.

The most striking fact is that a substantial fraction of the trajectories, 9 of 22, take start on the 'other side' of the MW-AG line of centers. The galaxies with these initial conditions move toward the center of the Local Group, initially, so that their initial velocities are negative, in Table 1. Their flow is a flow of contraction, not expansion, at that time. The galaxies with negative initial velocities gain considerable infall velocities near the center of the Local Group, that reach 180–300 km s^{-1}. Then they pass the central region of the group and begin to move from the center (continuing their motion in the same direction in space). In this way, the initial contraction flow transforms into the expansion flow.

During this transformation, galaxies gain also an additional velocity, — now it is a positive velocity of recession. The acceleration of this nature is not due to antigravity of vacuum; this is exactly the same dynamical effect of gravitational acceleration that was studied in details for an early dynamics of LG in the model of the Little Bang (Byrd et al. 1994). Violent gravitational interactions of the VLHF galaxies with MW and AG and LG as a whole are also similar to another picture of the early LG described recently by van den Bergh (2003).

Together with 7 galaxies that move outward the center initially with high (around 200 km s^{-1}) velocities (most probably, they were also accelerated earlier in the same manner), these 9 galaxies form a fast sub-flow of VLHF. A slow sub-flow of 6 galaxies starts its expansion with the velocities of 80–160 km s^{-1}. The initial conditions for both fast and slow sub-flows occupy an area in the radial velocity space from -277 to $+231$ km s^{-1} and an area in the radial distance space from 0.2 to 1 Mpc. Therefore, the initial spread of the velocities is measured by a figure of 650 km s^{-1} at that time. For comparison, at present the same 22 galaxies have velocities within a much narrower interval from 23 to 268 km s^{-1}, and so the spread is measured by 245 km s^{-1}.

There are no signs of the linear regularity in the velocity-distance relation, in the initial state of VLHF. For instance, the expansion rate (the ratio $\dot{R}/R$) estimated for individual trajectories prove to be in the interval from -932 to 700 km s^{-1} Mpc^{-1}, initially. So the initial spread of this quantity is measured by 1600 km s^{-1} Mpc^{-1}(!). This is a clear quantitative measure of highly disordered nonlinear initial structure of the flow. It may be compared with the present-day state of VLHF, at which the expansion rate is observed from 22 to 87 km s^{-1} Mpc^{-1}, and so the spread is only 65 km s^{-1} Mpc^{-1}.

The phase portrait (Fig. 2) of the initial VLHF reveals complex dynamics that can be understood within the framework of the Little Bang (Byrd et al. 1994). According to this framework, the formation of the Local Group and nearby galaxies, including ones that constitute now VLHF, is due to violent dynamics involving close passings, contact collisions and merging of many sub-galactic units in the volume of 1–2 Mpc across. In this process, the major fraction of the material falls into two major potential wells formed by the dark matter concentrations in the volume, while the VLHF galaxies represent only debris that AG and probably MW as well ejected from their common potential well into outer volume. The physical mechanisms of ejection are studied in details by Byrd et al. (1994).

It seems most probable that only accelerated ejected fragments (dwarf galaxies and sub-galactic units) were able to survive as individual physical objects in this violent environment and escape from the LG potential well out of the zero-gravity sphere. If so, the Little Bang dynamics was mainly responsible for the origin of the VLHF galaxies and for the initial conditions of their motions. The quantitative results given by Byrd et al. (1994) indicate that the velocities and distances in the initial state of VLHF (see columns 5,6 of Table 1) are quite feasible for the ejected bodies, in the violent dynamics of the Little Bang.

Note that some concrete features of the original version of the Little Bang model need to be re-considered now in the light of new observational data. However the idea of the violent dynamics for the early LG is in quite good agreement with the current data. A recently published picture (van den Bergh 2003) for the LG origin demonstrates the naturalness of the initial violent dynamics in a clear way.

4.3. Evolution of the Hubble ratio

Fig. 3 shows the Hubble ratio, or the time rate, $H_L = V/R$, which is the individual velocity-distant ratio for the VLHF galaxies, as functions of time. The convergence of the bunch of the 22 trajectories to the universal time rate is obvious from the figure: this is the major trend of the VLHF evolution which makes VLHF be essentially a cosmological phenomenon.

Fig. 4 shows the same for the 'imaginary' (no vacuum) trajectories. As is seen from the plots, the role of vacuum increases systematically with time, while the role of LG gravity is only decreasing. Meanwhile the same trend as in Fig.3 reveals in Fig.4 as well: even in the model without vacuum, the individual expansion rates tend to converge to a common one for all the galaxy sample. (The difference is only in numbers, and the dynamical effect of vacuum gives a higher mean Hubble ratio at present.) The similarity is completely due to the initial conditions which are the same for both models and – which is seemingly more important – resulted in the backwards calculations from the rather smooth observed Hubble law. Indeed, there is, generally, no reason to expect that a regular linear flow would arise from arbitrary initial distributions of distances and velocities for bodies moving in the gravitational field of the Local Group without vacuum.

In an additional set of simulations, we tried an example of a 'random' initial velocity-distance distribution for bodies in the close vicinity of the LG. Some of the bodies were captured by the LG gravity, while the others escaped and moved away from the group. It was found that the flow of the escaped bodies revealed an evolution to the regular linear velocity-distance relation only in the presence of cosmic vacuum. This trend was most obvious for larger (> 3 Mpc) distances from the center of the LG.

In the presence of vacuum, two effects are especially important. First, vacuum accelerates the motions of the VLHF galaxies by its antigravity. Second, acting as a time independent dynamical factor, vacuum tends to supply each individual galaxy of VLHF with one and the same expansion rate, independently of the galaxy initial kinematical states. Both physical effects are obvious from the consideration of the asymptotical state of the flow, in the

limit of large times, when the role of gravity vanishes and antigravity controls the flow completely.

In this limit, the solution for any individual radial trajectory has a form: $R(t) \propto \exp(H_V t); t \to \infty$, where $H_V = (\frac{8\pi G}{3}\rho_V)^{1/2}$. Therefore each individual time rate $H(t)_L$ tends with time to $V/R = \dot{R}/R = H_V = Const$ for any trajectory. Both effects mentioned above lead finally to the formation of the flow with the linear velocity-distance law: $\dot{R} = H_V R$, where the common time rate for the VLHF galaxies is constant in space and time and determined by vacuum only: $H_L = H_V$.

As for the Hubble global flow, similar considerations show that its asymptotical expansion rate is also determined by vacuum only: $H(t)$ tends to H_V when $t \to \infty$. Thus, asymptotically, VLHF and the global expansion flow become completely identical in their kinematical structure. This is the net ultimate result of the universal antigravity of cosmic vacuum on all spatial scales.

It seems especially remarkable that the present states of both VLHF and the global flow are not very far from the asymptotical state; this is seen, first of all, from the fact that the present-day observational value of $H_L = 72 \pm 15$ km s^{-1} Mpc^{-1} and the present-day observational value for $H = 65 \pm 10$ are both fairly close to the theoretical limit $H_V = 55 \pm 10$ km s^{-1} Mpc^{-1} (actually, all the three values are compatible with a common figure near, say, 60 km s^{-1} Mpc^{-1}).

5. Conclusions

Until quite recently, the structure and dynamics of the galaxy flow around the Local Group have remained poorly known because of the lack of reliable data on distances to most of the nearby galaxies. The recent high accuracy measurements of these distances have led to the discovery of the real structure of the fairly regular very local (≤ 3 Mpc) Hubble flow (Karachentsev et al. 2000, 2002, 2003). Basing on these data, we have started herein detailed quantitative studies of the physical nature of the phenomenon. An approach we try is suggested by the recent discovery of cosmic vacuum (Riess et al. 1998, Perlmutter et al. 1999). We have argued earlier (see the references in Sec.2) that cosmic vacuum is a key dynamical factor not only in the Universe as a whole, but also in our close vicinity in space where VLHF is observed.

As a first step in concrete realization of this approach, we have performed computer simulations of the history of the flow, its present and future states. The results of the simulations and their analysis have revealed two basic aspects of the dynamics of VLHF:

A) The force field that controls VLHF during almost all its history is dominated by the antigravity of cosmic vacuum at distances 1.5–2 Mpc from the Local Group center of mass. The ultimate dynamical state of the flow is entirely determined by cosmic vacuum with its perfect uniformity. The perfectly regular antigravity force field introduces regularity to the flow. The dynamical effect of cosmic vacuum leads asymptotically to the universal and constant in time expansion rate $H_V = (\frac{8\pi G}{3}\rho_V)^{1/2} = 55 \pm 10$ km s^{-1} Mpc^{-1}. The present state of the flow is not far from its asymptotical state because its observed Hubble rate is near the asymptotical value H_V.

B) The evolutionary history of VLHF starts at the epoch of the Local Group formation some 12.5 Gyr ago. At that time, the flow galaxies, together with the forming major galaxies of the group and many sub-galactic units, participated in violent nonlinear dynamics with collisions and merging. VLHF was formed by relatively small units that survive accretion by the major galaxies and managed to escape from the gravitational potential well of the Local Group. Our simulations show that a typical VLHF member galaxy gained escape velocity from the highly non-stationary gravity fields of the forming group and a velocity larger than some 200 km s^{-1} enabled it to reach the vacuum-dominated outer region. The simulations we produced do not describe the violent dynamics of the forming Local Group. However they give definite indications to the very existence of this dynamics. It is a special complex problem to re-construct the violent initial dynamics in the local volume in all its completeness; the Little Bang model (Byrd et al. 1994) and the picture presented by van den Bergh (2003) provide important insights to the problem and give the basic grounds for such a study.

The approach developed in this paper can be extended (and we will report the results later) to larger volumes around the Local Group. One can expect both a similarity to VLHF and some specific differences for the distances, say 10–100 Mpc which are still within the cell of uniformity of the galaxy spatial distribution. The observed bulk motion with 500–600 km s^{-1} velocity is one of the major features on these scales. The differences may be mostly in the initial conditions for the flow on these scales. But the similarity may definitely be due to cosmic vacuum with its universal antigravity. It is perfectly uniform cosmic vacuum that is suggested to be the major physical agent affecting the expansion flow everywhere (including the bulk motion — Chernin, 2001), from a few Mpc to the observation horizon.

Another interesting direction for further computational studies is provided by an opportunity of a more general form of cosmic antigravity which is due to dark energy with a time variable density. It was argued in Baryshev et al. (2001) that a variable dark energy, especially such 'coupled' with matter would better explain the small local velocity than the classical vacuum; this was because of the fact that the gravity dominated region was then smaller in the past. In this case, the model for VLHF would include a decreasing dark energy density which would make the flow dynamical background essentially non-stationary, – contrary to the model presented above.

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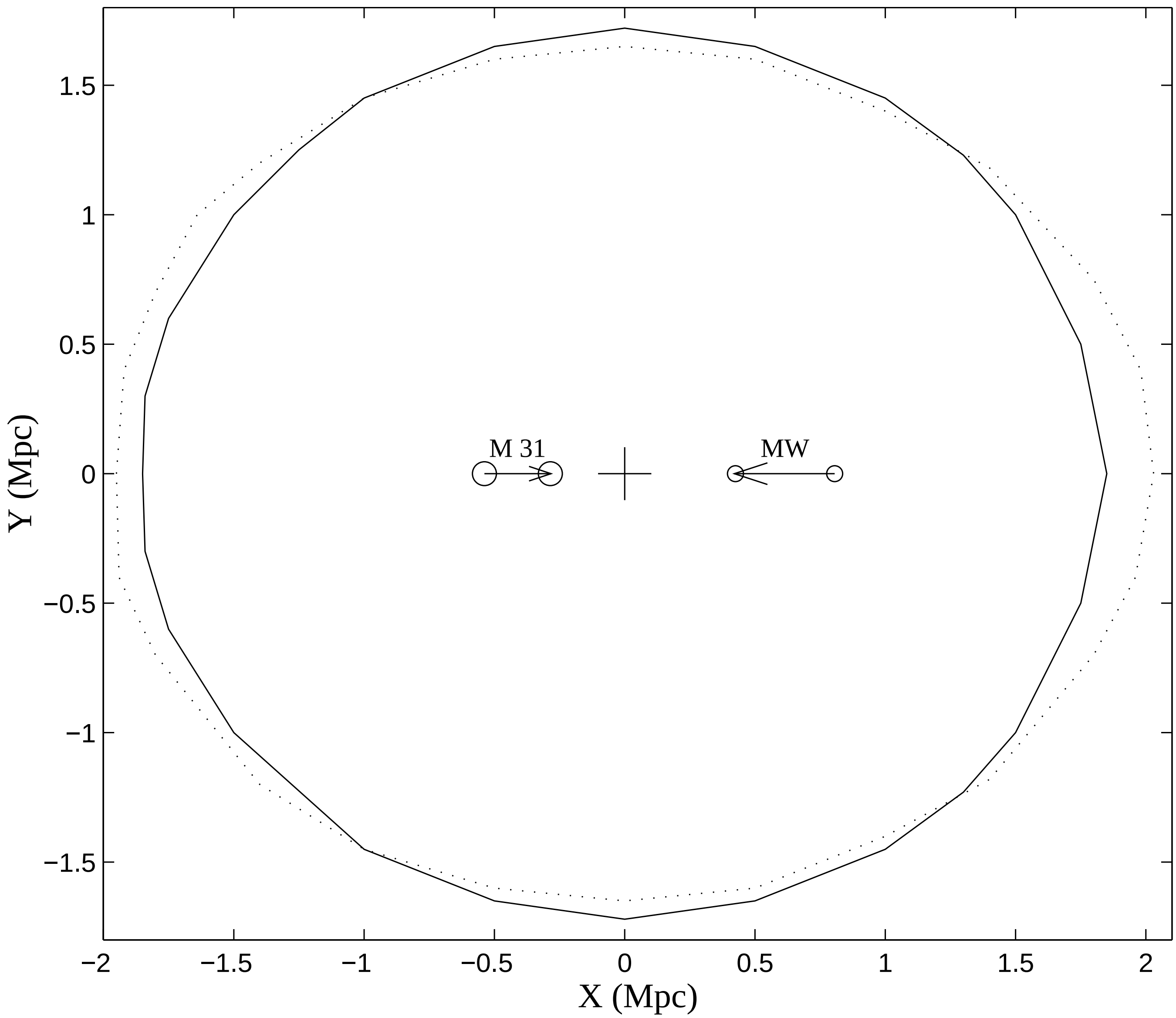

Fig. 1. Zero-gravity surface around the Local Group now (solid line) and 12.5 Gyr ago (dashed line).

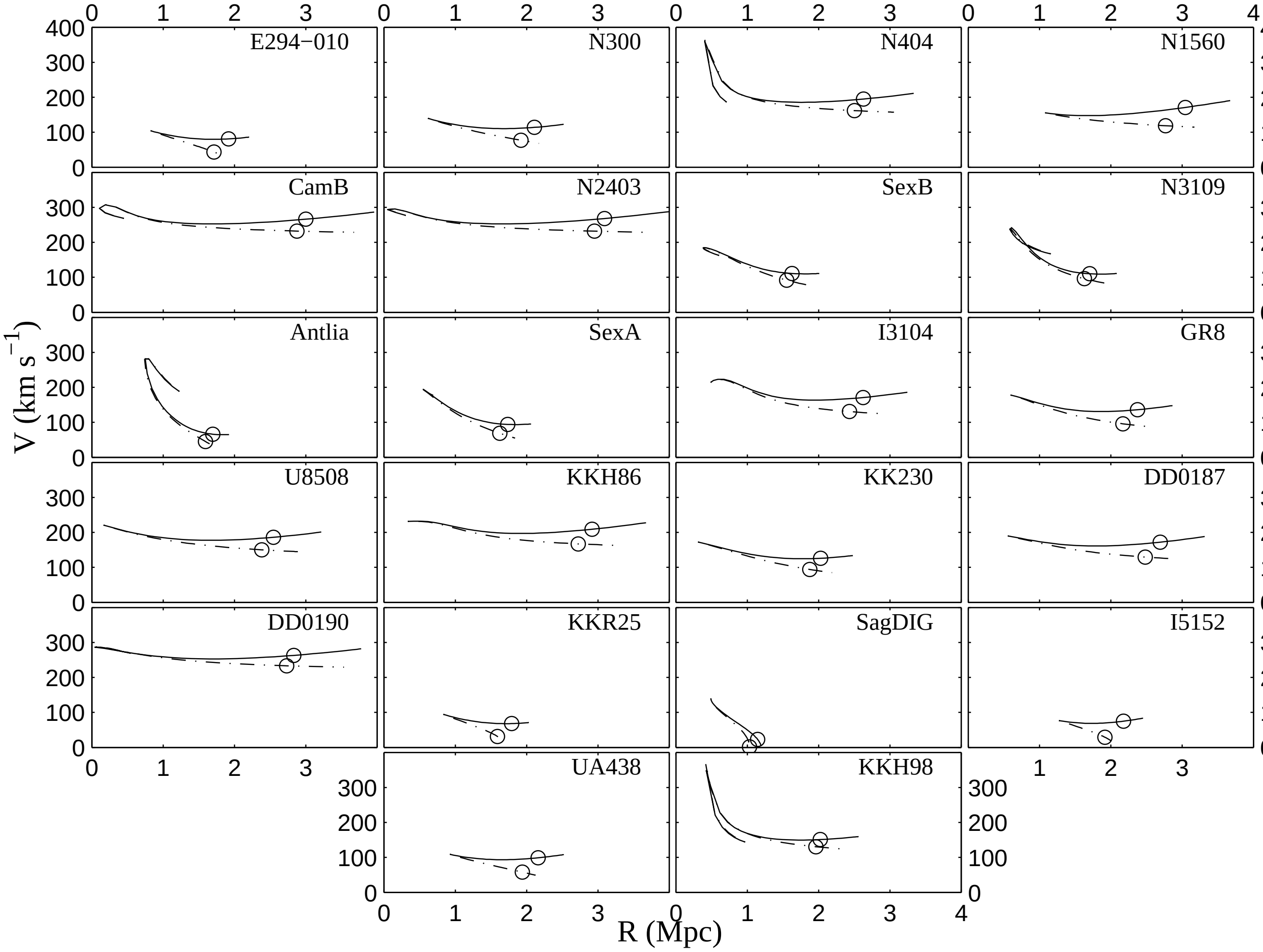

Fig. 2. The phase portrait of the the very local Hubble flow: radial velocity vs. radial distance plots for 22 galaxies of the flow – solid lines. For comparison: same for trajectories calculated with the same initial conditions 12.5 Gyr ago, but without cosmic vacuum – dashed lines. Circles indicate the present state.

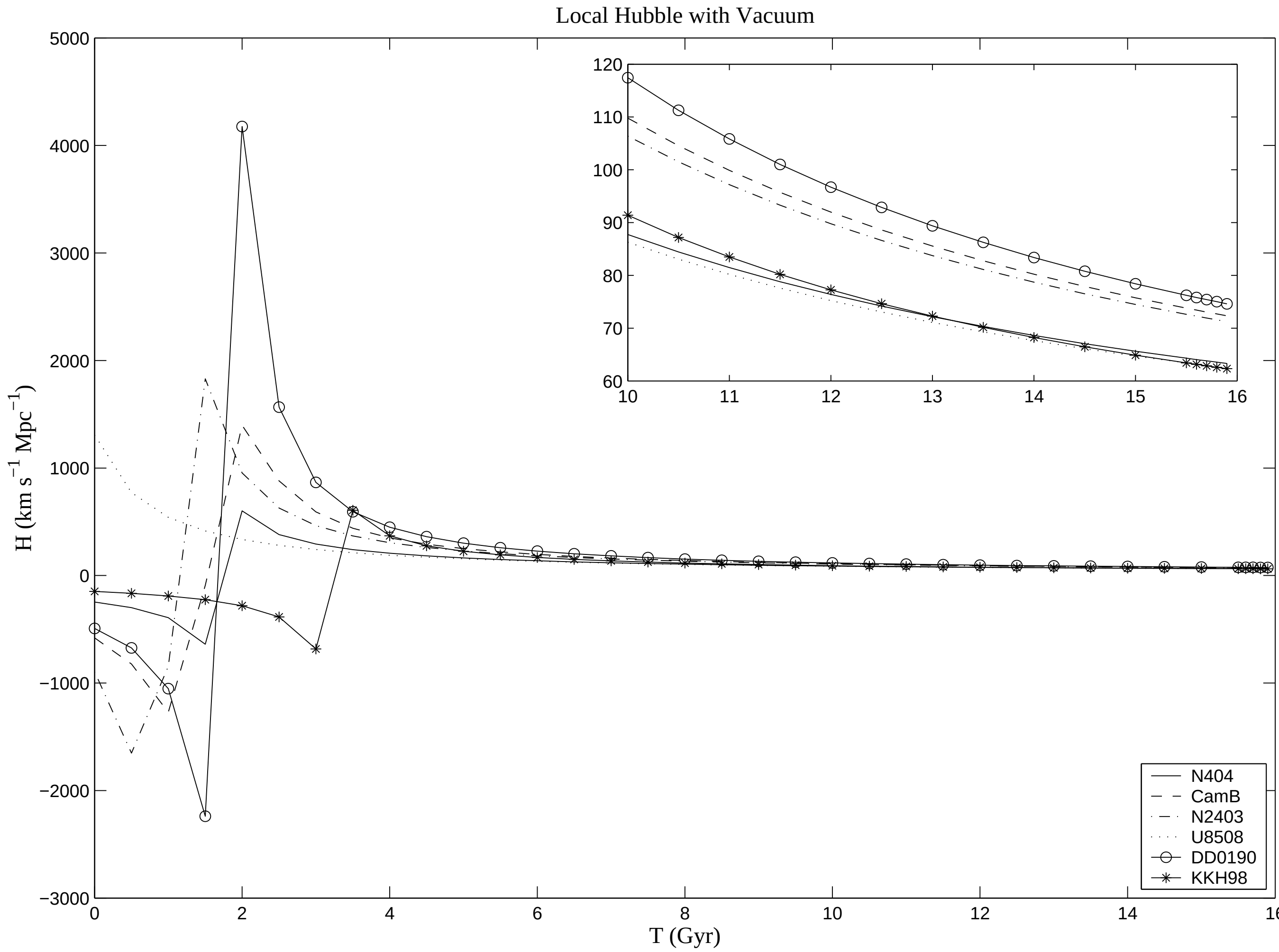

Fig. 3. Velocity-distance ratio for the galaxies of the very local Hubble flow as a function of time.

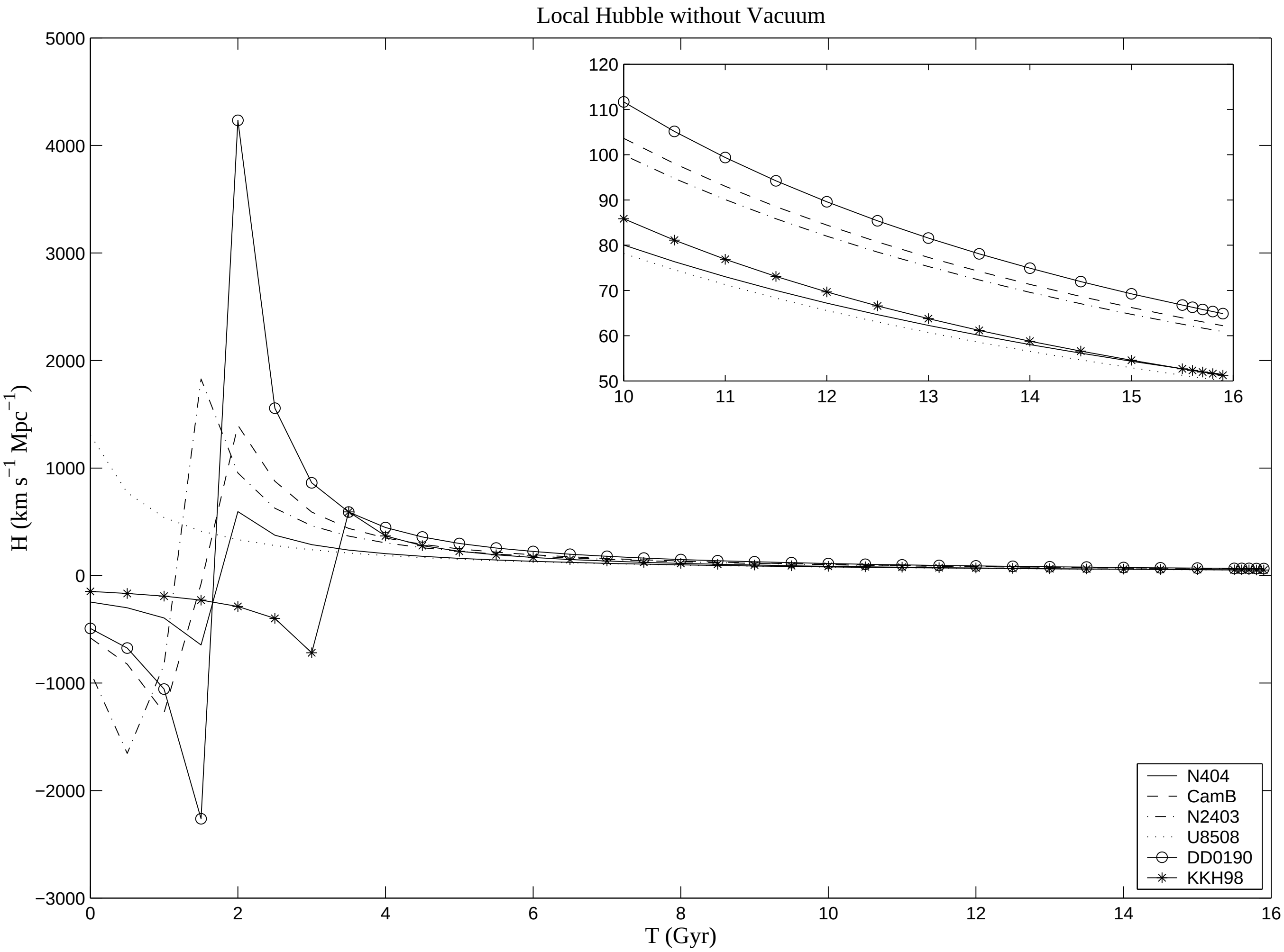

Fig. 4. For comparison: same for trajectories calculated with the same initial conditions 12.5 Gyr ago, but without cosmic vacuum.